

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE May 95		3. REPORT TYPE AND DATES COVERED	
4. TITLE AND SUBTITLE Evaluation of techniques for computer modeling & Real time control of a horizontal axis wind turbine blade				5. FUNDING NUMBERS	
6. AUTHOR(S) Alan Wesenberg				8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/CI/CIA	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFIT Students Attending: University of Colorado				95-033	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) DEPARTMENT OF THE AIR FORCE AFIT/CI 2950 P STREET, BDLG 125 WRIGHT-PATTERSON AFB OH 45433-7765				10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release IAW AFR 190-1 Distribution Unlimited BRIAN D. GAUTHIER, MSgt, USAF Chief Administration				12b. DISTRIBUTION CODE F	
13. ABSTRACT (Maximum 200 words)					
19950615 055					
14. SUBJECT TERMS				15. NUMBER OF PAGES 22	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT		18. SECURITY CLASSIFICATION OF THIS PAGE		19. SECURITY CLASSIFICATION OF ABSTRACT	
				20. LIMITATION OF ABSTRACT	

EVALUATION OF TECHNIQUES FOR COMPUTER MODELING
AND REAL TIME CONTROL OF A HORIZONTAL AXIS WIND TURBINE BLADE

Alan Wesenberg
Department of Aerospace Engineering Sciences
University of Colorado
Boulder, Colorado

Accession For	
NTIS CRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

ABSTRACT

Wind power generating turbines operate under constant as well as rapidly changing conditions. With fixed pitch blades, many wind turbines are allowed to operate regardless of wind conditions as long as they are able to produce more electricity than it takes to get them started. However, the lifecycle of the turbine blades is often much shorter than expected because of the unsteady aerodynamic environment under which they rotate. Therefore, the National Renewable Energy Laboratory (NREL) has implemented a testing program to determine the aerodynamic conditions, and the frequency with which they occur, which cause the largest amount of fatigue on their variable pitch, three bladed downwind horizontal axis wind turbine (HAWT). Different techniques will be examined for analytically modeling the flow conditions with separation over a rotating turbine blade. Then, some different techniques for implementing a feedback control loop will be investigated to optimize the movement of the variable pitch blades on the NREL HAWT. The different methods analyzed will fall in the two-dimensional, incompressible area with most also being for steady state conditions. The final objective is to provide the reader with a background in dealing with the aerodynamic conditions surrounding a rotating wind turbine in an unsteady aerodynamic environment.

TABLE OF CONTENTS

Abstract	i
Table of Contents	ii
List of Symbols	iii
Introduction	1
Background	3
Techniques for Modeling the Flow on a Computer	6
Techniques for Implementing a Control Scheme	11
Summary	15
References	16
Appendix A	18

LIST OF SYMBOLS

C_f	Coefficient of Friction
C_p	Coefficient of Pressure
H	Shape factor of the boundary layer, $H = \delta^*/\theta$
p	Static Pressure (measured on the blade surface)
p_∞	Reference Static Pressure
p_{stag}	Static Pressure measured at the stagnation point on the blade's surface
p_o	Total Pressure (measured from pitot probe)
q_∞	Dynamic Pressure
R	Perfect gas constant
Re	Reynolds Number
T	Freestream absolute temperature
t	time
u	Streamwise velocity component
u_e	Velocity at the edge of the boundary layer, corresponds to that from potential flow
v	Velocity component in the y-direction
V_∞	Local Freestream velocity
x	Coordinate, streamwise direction
y	Coordinate perpendicular to the x-direction
δ	Thickness of boundary layer or shear layer
δ^*	Displacement thickness of boundary layer
θ	Momentum thickness of boundary layer
μ	Dynamic viscosity
ν	Kinematic viscosity
ρ	Air density
τ_w	Shear stress at the wall

INTRODUCTION

Harnessing the power of the wind as a clean renewable energy source has been a goal of researchers and industry for many years. The origin of windmills to utilize the wind to perform work is a centuries old concept. However, it is not until recently that researchers have reoriented their focus from the mechanics of building wind turbines to that of optimizing the wind energy production while increasing the blade lifecycles. Wind turbines are obviously placed in locations where there is a strong flow of air on a regular basis. Any person who has ever stood or driven in the areas where wind turbines operate, knows how rapidly the wind can change velocities and directions. This unsteady aerodynamic environment leads to dynamic loading on turbine components, such as generators and blades, "far in excess of their design loads" [1]. The unsteady aerodynamic effects include "dynamic inflow, turbulence, and dynamic stall" [1] which decrease the lifetime of major wind turbine components from their 20-30 year design lifetime [2] quoted in [1].

The conditions under which a wind turbine operates create stalled sections of the blade along with portions that have completely attached flow. In addition to the normal statically stalled condition, the turbine blades also encounter a dynamic stall situation. Static stall is defined as the loss of lift over a wing due to flow separation. Dynamic stall similarly results in a loss of lift, however, it is a cyclic phenomenon with detachment of the flow followed by reattachment. Furthermore, as described by McCroskey [3] quoted in [4] "Dynamic stall is the phenomenon under which a vortex is seen to travel from leading to trailing edge when flow separation occurs." The existence of dynamic stall on a rotating turbine blade is evidence of aerodynamic loads which are exceeding the design parameters. In the past there has been little concern about the existence of stalled portions of the turbine blade because there were few methods to alleviate the problem and their costs were impractically high or the method was simply not implementable. With the decreasing costs and increasing speeds of microprocessors, it is now possible that control schemes can be implemented to improve the performance of turbine blade stall.

Before attempting to improve wind turbine performance, it had to be determined that dynamic stall occurred often enough to warrant the expense. Shipley, et al, [1] examined the dynamic stall phenomenon on the National Renewable Energy Laboratory's (NREL) "Combined Experiment" on a downwind horizontal axis wind turbine (HAWT) and statistically determined that it occurred in over 50% of their test cycles. It is evident then, that dynamic stall occurs with a frequency that justifies the expense of implementing a control scheme to increase the lifecycle of turbine blades in addition to improving the efficiencies of wind turbines. This paper examines some starting points for computer modeling the flow over a turbine blade and progressing that model towards use in a feedback control scheme. The intent is to inform the reader of the nature of the aerodynamic phenomena which control the flow over the turbine blade. In order to implement an adaptive control scheme it is necessary to start with a simplified model of the flow and follow that by more complex models which ultimately require large numbers of empirically derived constants. However, it is possible that a simplified model may suffice for a reliable control algorithm which is relatively easy to implement.

BACKGROUND

The freestream wind velocity under which turbine blades rotate is in an incompressible regime because it is almost always under Mach 0.1. This freestream velocity translates into a reasonable assumption that the flow is incompressible over the turbine blades. The existence of a constant density term simplifies the modeling of the flow and is a valid assumption for most wind turbines. C. Hansen of the University of Utah verified that the errors created by making the incompressible assumption are negligible when compared with calculations made for compressible, isothermal ideal gas [5]. However, allowing the incompressibility assumption does not eliminate the dynamic and transient events from the complete model. Furthermore, the Reynolds number over the surface of turbine blades is generally greater than 3×10^5 , which means that the flow can be considered to be turbulent. However, the flow probably has some regions of laminar flow towards the leading edge of the blade. Also, for small freestream wind velocities the flow could be highly laminar. This is especially true for the NREL S809 airfoil which is designed to operate with a maximum amount of laminar flow.

Regardless of the type of flow over the blade, there is still the possibility of flow separation and the resulting stalled condition when the airfoil experiences increases in angle of attack. The reason for the separation is that the fluid in the boundary layer has low kinetic energy. Therefore, it is more difficult to move against a pressure gradient. However, a turbulent boundary layer has a greater energy level and it is therefore more difficult for the flow to separate than in a laminar boundary layer. This is an advantage of the flow conditions on a wind turbine. The separation point on a body can be determined through different metrics. Ultimately, the point where the shear stress goes to zero is the point of separation. This location can similarly be denoted by $\partial u / \partial y = 0$ which is the shear stress without the viscosity term. Furthermore, static stall occurs in the existence of an adverse (positive) pressure gradient. Therefore, the static pressure distribution over the turbine blade is of paramount interest in order to obtain the necessary parameters to evaluate the aerodynamic conditions. However, since velocity and pressure are interrelated, the velocity distribution could be measured or modeled directly. For

measurement on a wind turbine, pressure data is the only realistic method because using multiple hot wire or hot film anemometers on the blade surface for direct velocity measurement would disrupt the flow too much. Furthermore, the coefficient of pressure is usually the metric used to determine when dynamic stall is probably occurring. Therefore, when producing an analytical model or implementing a control scheme for a wind turbine, it would be normal to work with a pressure distribution.

NREL's Combined Experiment three-bladed, variable pitch, downwind horizontal axis wind turbine is a 5.05 meter radius machine with one fully instrumented untwisted blade (see Appendix A for basic dimensions and layout). In addition to the turbine, there is also an upwind array for measuring the upstream wind velocity and direction along with ambient air conditions. For a complete discussion of the instrumentation and test setup see reference [6]. The most significant data collection is from the chordwise static pressure ports. Coupling this data with that from the total pressure pitot tubes, the velocity can be determined for the same chordwise locations as the static pressure. Velocity is determined from the following equation:

$$p_o - p = q_\infty = \frac{1}{2} \rho V_\infty^2 \quad (1)$$

However, according to Shipley, et al. [7] the measurement of the total pressure is out of phase with the simultaneous values for static pressure because the total pressure probes are 0.62 meters in front of the turbine blade leading edge. However, when adjusting for the probe location the total pressure measurement can be used to calculate the local velocity values as long as the angle of attack of the instrument is below 40° .

An alternate technique was developed by Shipley, et al. [7] to calculate the dynamic pressure independent of a total pressure measurement. This method is based on the knowledge that for incompressible and irrotational flow, there exists a stagnation point (local velocity equals zero) where $C_p = 1.0$ where

$$C_p = \frac{p - p_\infty}{q_\infty} \Rightarrow q_\infty = p_{stagnation} - p_\infty \quad (2)$$

The results from this method correlate well with the calculation based on the total and static pressure measurements and corrected for probe location. However, with only one dynamic pressure value for each spanwise location, there can be no velocity distributions in the chordwise direction. Therefore, measuring the total pressure maybe the only method which will provide the necessary velocity profile for implementing some control schemes.

With a pressure coefficient determined, the occurrence of dynamic stall can be evaluated. When there is a rapid change in local angle of attack, the turbine blade section can surpass the static stalled condition and enter a dynamic stall. As Shipley, et al. [1] writes, "Turbulence, shifts in wind direction or magnitude, wind shear, or upstream flow disturbances can alter the local velocity, and hence, create blade angles of attack changes sufficient to drive dynamic stall." This rapid change in local angle of attack will cause the development of a peak pressure coefficient near the leading edge of the blade section. Therefore, choosing a particular value of C_p which represents the occurrence of dynamic stall is a straight forward approach towards recording its existence. For the Combined Experiment, the blade airfoil section was tested in the Colorado State University wind tunnel and the maximum value of suction recorded was $C_p = -5.0$ [1]. However, this testing was performed under steady aerodynamic conditions in the wind tunnel which are unlike those found in normal wind turbine operating environment. When the analysis was performed on the data from NREL's Combined Experiment, a value of $C_p = -10.0$ was chosen as the minimum suction value for measuring the occurrence of dynamic stall [1]. Since this number is twice that of the wind tunnel data, there is the possibility that more dynamic stall events occur with less suction on the leading edge of the turbine blade. Therefore, this criterion chosen for dynamic stall determination will necessarily be refined for the development of an optimal control scheme.

TECHNIQUES FOR MODELING THE FLOW ON A COMPUTER

One place to begin the analysis of modeling flow over a rotating turbine blade is to start with the basic laminar, steady, incompressible, two-dimensional case. This is actually quite useful when making a complete model of the flow since part of the blade will probably start with laminar flow and continue through transition to fully developed turbulent flow. Therefore, a good solution would include laminar flow patched together with transition and turbulent models. Even though it is highly unlikely that the flow would separate in the laminar region, to be complete, a laminar flow separation algorithm will be discussed. Laminar flow separation is relatively independent of Reynolds number as long as the flow remains entirely laminar. This means that the separation point becomes a fixed geometric point for a specific body at a set angle of attack [8]. Furthermore, most laminar separation solutions rely on manipulating the boundary layer equations to get a result.

Stratford Criterion

Stratford [9] solved the boundary layer equations in two parts by separating the inner and outer layers. The inner layer is dominated by the viscous forces, but they are balanced by the pressure gradient. "Therefore, a transition across the layer causes the pressure forces to be balanced by viscous forces at the wall and by inertia forces at the outer edge of the boundary layer" [8]. This allows the effects of the pressure gradient to be considered separate from the effects of viscosity in the outer layer. This method relies on the knowledge of potential flow distribution around the body. The Stratford criterion for separation as modified by Curle and Skan [10] is

$$\left[\bar{x}^2 C_p \left(\frac{dC_p}{d\bar{x}} \right)^2 \right]_s = 0.0104 \quad (3)$$

$$\bar{x} = x_{eq} + x_s \quad (4)$$

where x_s is the distance measured from the maximum potential velocity point to laminar separation and x_{eq} is the equivalent length upstream of the maximum potential velocity given by

$$x_{eq} = \int_0^x \left(\frac{u_e}{u_{e_{max}}} \right)^{8.17} dx \quad (5)$$

$$C_p = \frac{p - p_{min}}{\frac{1}{2} \rho u_{e_{max}}^2} \quad (6)$$

Since this method is based on the inviscid potential flow solution, it is easy to implement when limited data is known about the boundary layer growth over the body. Most methods, including this one, do not provide good results at low angles of attack when compared with experimental results, but separation is more of a problem when the body is under a high angle of incidence to the freestream. The Stratford method provides a relatively easy solution to the laminar separation problem, but it is only for a steady state case to provide a baseline to which an unsteady solution can be compared. However, when attempting to examine unsteady conditions, the equations are the nonlinear boundary layer equations. Therefore, the ultimate direction is to integrate the boundary layer equations for incompressible flow. This method is examined in the next section of the paper.

Garner Criterion

Now, since the flow is most likely to be turbulent when it undergoes separation, an algorithm will be examined to model this condition. The Garner criterion [11] for turbulent flow separation describes the skin friction as a power law and the following two parameters:

$$\Theta = \theta \cdot \text{Re}_\theta^{1/n} \quad \text{and} \quad \Gamma = \frac{\Theta}{u_e} \frac{du_e}{dx} \quad (7)$$

where x is the distance along the wall and $n = 6$. Now, taking transition into effect Garner developed the momentum and empirical equations

$$\frac{d\Theta}{dx} = \frac{7}{6} \left[\zeta - \Gamma \left(H + \frac{13}{7} \right) \right] \quad (8)$$

$$\Theta \frac{dH}{dx} = e^{5(H-1.4)} [-\Gamma - 0.0135(H-1.4)] \quad (9)$$

where $\zeta = (\tau_w / \rho u_e^2) \text{Re}_\theta^{1/n}$ [8]. Solution of the differential equations (8) and (9) yield a value of H . When $H = 2.6$ separation is predicted to occur. The relationship between Γ and $\Theta(dH/dx)$ is

empirically defined for different values of H in reference [11]. The procedures for calculation using the Garner criterion (taken directly from reference [8]) are as follows:

1. Determine the development of the laminar boundary layer before transition.
2. Decide at which point on the surface transition takes place, if at all.
3. Compute the value of Θ immediately after transition. (The value of θ at the position of transition is determined from Step 1, and θ is continuous through transition.)
- 4a. If transition occurs at or downstream from the position of maximum velocity, assume that $dH/dx = 0$ there, i.e., that $H = 1.4 - (\Gamma/0.0135)$ immediately after transition.
- 4b. If transition is upstream from the point of maximum velocity, assume that H is constant between the positions of transition and the maximum velocity. The value of Θ at the position of the maximum velocity is given by

$$u_{e_{\max}}^k \Theta = \left[u_e^k \Theta \right]_{tr} + 0.007623 \int u_e^k dx$$

where the subscript tr denotes values at the assumed position of transition and the integral is taken from the position of transition to the point of the maximum velocity and $k = \frac{7}{6}H + \frac{13}{6}$.

5. Finally, determine the point of separation by integrating equations (8) and (9).

The Garner criterion provides a rapid solution to the turbulent flow separation problem with relatively reliable prediction when compared with experimental data [8].

Total Variational Diminishing Turbulence Model

A second turbulent model has been developed specifically for the NREL S809 airfoil which is the one used in the Combined Experiment. This research is currently being performed by Yang, et al. [12] at the Michigan Technological University. They are using a spatially second-order symmetric TVD (Total Variational Diminishing) scheme to model the flow field for the NREL S805 and S809 airfoils. Their model remains in the steady, two-dimensional, viscous, incompressible, turbulent flow regime followed by the previous model. However, their model does not predict when the airfoil will undergo separation, but rather models the pressure distribution over the entire airfoil. The resulting data compares well with that from Delft University of Technology wind tunnel experimental data except when the airfoil is at a high angle

of attack and a large amount of flow separation occurs [13]. Therefore, Yang, et al. are continuing their research into better turbulence models which will allow prediction of flow characteristics beyond statically stalled conditions. Furthermore, their method still eliminates the unsteady terms from the governing equations. In the absence of the unsteady terms, there is no chance of modeling the dynamic stall characteristics which are found in the field testing results of the Combined Experiment.

All of the previous models dealt with two-dimensional models of airfoils. Knowing that there are still problems with this level of research makes it difficult to move towards fully three-dimensional flow models. However, some models have been developed which use two-dimensional airfoil data to predict turbine performance. According to Peter Tu [14] from the Wind Energy Program at NREL, the accuracy of the PROP and LSWT codes are poor when involving high wind velocities and high angles of attack on the NREL Combined Experiment. Part of the problem comes from the fact that the necessary airfoil data from the wind tunnel tests is not reliable in the post stall region because different tests have given results which are too high or too low when compared with the Combined Experiment results. Therefore, if analytical methods can be improved upon, such as the previously discussed method by Yang, et al. [12], the reliability of the PROP AND LSWT codes could be increased. In addition, the analytical models developed by Dini, et al. [15,16] have made progress "in modeling airfoil stall and post-stall characteristics using an interactive boundary-layer and trailing-edge vortex analysis method" [14]. In addition to improving the airfoil data, Tu also recommends developing an accurate tip loss model for the wind turbine performance prediction codes [14].

One of the major factors controlling the complexity of three-dimensional analysis over that of two-dimensional is the problem associated with the different flow conditions at the tip. This problem is accentuated when dealing with rotating propellers because boundary layer separation occurs at greater angles of attack than when they are stationary as in a wind tunnel. This phenomenon is explained by the additional fluid acceleration in the flow direction caused by Coriolis force which in effect provides a favorable (negative) pressure gradient. The Centrifugal

forces cause less fluid to be transported towards the blade tip from the root than is lost outwards. Therefore, the boundary layer is thinner towards the blade tip which allows higher angles of attack before separation [17]. Muesmann writes in his thesis that transition occurs at a much lower Re on rotating propellers when compared with a stationary blade [18]. This decrease in transition Re can largely be attributed to centrifugal force. Therefore, obtaining a good post stall model does not necessarily mean that the results from a turbine prediction code would perform any better than a two-dimensional model unless there was a good tip loss model. Furthermore, the entire model would have to take into account all of the peculiarities of a rotating turbine blade which are different from those of the same blade stationary in a wind tunnel even accounting for three-dimensional effects. Therefore, the two-dimensional codes must be improved before moving on to accurate three-dimensional rotating turbine blade prediction models.

The two areas of concern for two-dimensional computer flow models are 1) the integration of better turbulence models and 2) the inclusion of unsteady aerodynamic terms. Once these problems are addressed, the ability of a computational fluid dynamics code to model dynamic stall would be greatly enhanced.

TECHNIQUES FOR IMPLEMENTING A CONTROL SCHEME

After seeing the challenges which face the modeling of the flow over a rotating turbine blade it is hard to imagine establishing a control scheme to optimize the energy output and longevity of the components of a wind power generator. However, there are some techniques which allow starting at a basic level to determine which parameters of those that govern the flow, significantly impact the optimization of the control of the turbine blade.

Preston Tubes

One a simple method determined by Preston [19] relies on the fact that at the point of separation of the flow, the skin friction becomes zero. Therefore, measurement of skin friction is a way to allow feedback to a control loop which will maintain attached flow by modifying the pitch of the blade. It must be assumed that the boundary layer over the blade is turbulent and the region near the surface follows the log "law of the wall." Then, according to Preston [19] a pitot tube can be placed in contact with the surface and wholly immersed in the law of the wall region. The difference between the measured pitot pressure P and the measured static pressure p must depend only on ρ , v , τ_w , and d (the outer diameter of the tube). Based on dimensional reasoning, a relation can be developed such as

$$\frac{(P - p)d^2}{\rho v^2} = F\left(\frac{\tau_w d^2}{\rho v^2}\right) \quad (10)$$

Experiments have been performed for a flat plate which determined the function F and the resulting relationship as

$$\log_{10}\left[\frac{\tau_w d^2}{4\rho v^2}\right] = -1.366 + 0.877 \log_{10}\left[\frac{(P - p)d^2}{4\rho v^2}\right] \quad (11)$$

Young [20] writes, "Because of the small uncertainties in the values of the constants involved the method cannot be relied upon to be in error by less than 5% (as is the case with the Clauser plot method) but it has been found to have wide applicability and its simplicity is a major asset."

Therefore, measuring P , p , V_∞ , and T and knowing ρ , d , τ_w can be determined. The shear stress at the wall is the direct component in the skin friction coefficient

$$C_f = \frac{\tau_w}{q_\infty^2} = \frac{\tau_w}{\frac{1}{2} \rho V_\infty^2} \quad (12)$$

This method would require experimentation to improve the empirical function F. Furthermore, one or more pitot tubes would have to be placed on the blade with telemetry to the control computer inside the generator housing. The freestream velocity could be measured by a pitot tube on the generator housing. A temperature measuring device would also be located here. Knowing the temperature and pressure, the density and kinematic viscosity can be determined

$$\rho = \frac{p}{RT} \quad \mu = \frac{CT^{3/2}}{T+S} \quad \nu = \frac{\mu}{\rho} \quad (13)$$

where C and S are known constants for the particular fluid.

Using a generic setup such as the previous one would be relatively inexpensive and with the small number of parts would require a low maintenance. However, the existence of a pitot tube in the flow over the turbine blade would disrupt the smooth surface and possibly cause premature separation. Furthermore, this method would be restricted to steady conditions and would therefore be unable to detect dynamic stalling conditions which occur rapidly. Overall, using a Preston tube to quantify an oncoming stalled condition would be impractical since it would require empirical testing to check if it is even a valid method to use with a rotating turbine blade. If the method could be validated, then it might be used as a baseline for other empirical tests of control algorithms.

Prandtl Boundary Layer Equations

The biggest downfall of the Preston tube method is that it does not allow a real time control scheme with unsteady conditions which is the primary reason for developing a variable pitch or otherwise controllable wind turbine system. One way to introduce the unsteadiness back into a method is to start with the boundary layer equations for a flat plate in two-dimensional, incompressible, unsteady flow that were derived by Prandtl in the early part of the 20th century. The dimensional quantities are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (14)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \frac{\partial^2 u}{\partial x^2} \quad (15)$$

$$\text{Boundary Conditions } y=0: u=0, v=0; \quad y=\infty: u=U(x) \quad (16)$$

$U(x)$ is the velocity determined from potential flow

These equations are derived by simplifying the two-dimensional Navier-Stokes equations by estimating the order of magnitude of each term. Equation (14) is the continuity relationship and remains unchanged. Equation (15) comes from the momentum in the x direction. To arrive at this second equation for the momentum of the boundary layer, it is assumed that the change of v and p in the y direction is equal to zero. This is a good approximation for boundary layer flows that remain attached and do not have a hypersonic Mach number [21]. Furthermore, equations (14) to (16) remain applicable to curved surfaces as well as flat plates when the surfaces do not have sharp edges [22].

In order to satisfy equation (16), it is necessary to determine the potential flow which is the inviscid portion of equation (15) with no velocity gradient in the y direction. Also, $u=U$ which is the velocity at the edge of the boundary layer determined by potential flow. This inviscid flow does not come in contact with the airfoil because of the existence of the boundary layer and is represented as:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x} \quad (17)$$

In order to represent a steady flow case, $\partial/\partial t$ terms are set to zero in equations (15) and (17). A steady state flow condition reduces (17) to Bernoulli's equation

$$p + \frac{1}{2}\rho U^2 = \text{const} \quad (18)$$

where all quantities are dimensional.

Regardless of the steadiness of the flow, the pressure distribution is a known quantity. Therefore, the u and v velocity terms are the only unknowns if the flow is steady. In an unsteady flow, the time derivatives must come from a known function. Therefore, (14) and (15) form a simultaneous system of two equations and two unknowns. As previously noted one of the assumptions for using the simplified two-dimensional Prandtl boundary layer equations is that the

flow remains attached. Therefore, this model could allow the development of a feedback control loop that will prevent separation from occurring, but would be unable to accurately model the flow in a post stall environment.

The latter method will be a useful starting point for developing a feedback control scheme to optimize the performance and minimize loading from dynamic stall by modifying the blade pitch of the NREL Combined Experiment HAWT. Since pressure data is readily available the pressure coefficient can be calculated in real time as a feedback element to increase or decrease the blade pitch as necessary. However, one variable which has yet to be addressed is the yaw angle that the turbine has with respect to the oncoming wind as it changes directions. This is one parameter which has not been entrained into the control model, but could have some impact on the control algorithm. However, once this initial control algorithm is in place, the effect of the yaw angle may become more apparent. Then, more detailed control algorithms may be developed. Furthermore, a yaw control loop could be introduced to drive this angle to zero in an attempt to eliminate the effect of the yaw angle.

SUMMARY

Different techniques were examined for computer as well as control modeling of the flow around two-dimensional rotating turbine blades. The primary concern lies in the area of flow separation which occurs in two different modes, static and dynamic stall. The static stall reduces the performance of the wind turbine, but does not cause structural problems. However, the dynamic stall is one of the primary drivers of a shortened lifecycle of the turbine blades. As Bass writes, "The critical design factor is the fatigue property of the blade and the need to keep vibratory stresses within acceptable limits" [23]. The real conditions existing in a field test such as NREL's Combined Experiment may be too complex to model on the first or even the fifth try, but each time the method can improve on earlier shortcomings and probably discover more areas for improvement. Therefore, picking the basic, very simplified models as starting points with all of their deficiencies is probably the wisest starting point for development of computer and control models for the NREL Combined Experiment downwind HAWT. Then, if these basic models are successful, more advanced computer models and control techniques can be used to handle the more complex flow problems.

REFERENCES

1. Shipley, D. E., et al., "Dynamic Stall Occurrence on a Horizontal Axis Wind Turbine Blade," as presented, 14th ASME/ETCE Wind Energy Symposium, 1995.
2. Lynette, R., "California Wind Farms: Operational Data Collection and Analysis," SERI/PR-217-3489, NREL, Golden, CO, 1989.
3. McCroskey, W. J., "The Phenomenon of Dynamic Stall," NASA Report TM-8124, 1981.
4. Slepiski, J. E., and R. H. Kirchhoff, "An Investigation of Stall on a Rotating Wind Turbine Blade," as presented, 13th ASME/ETCE Wind Energy Symposium, 1994.
5. Miller, M. S., et al., "Determination of Data Reliability for Phase II of the Combined Experiment (Draft)," National Renewable Energy Laboratory, Golden, CO, 1994.
6. Butterfield, C. P., et al., "Combined Experiment Phase I: Final Report," NREL/TP-257-4655, National Renewable Energy Laboratory, Golden, CO, 1992.
7. Shipley, D. E., et al., "Techniques for the Determination of Local Dynamic Pressure and Angle of Attack on a Horizontal Axis Wind Turbine," NREL/TP-442-7393, National Renewable Energy Laboratory, Golden, CO, 1994.
8. Chang, P. K., *Control of Flow Separation*, McGraw-Hill Book Company, New York, 1976.
9. Stratford, B. S., "Flow in the Laminar Boundary Layer near Separation," ARC Technical Report R&M 3002, 1957.
10. Curle, N. and S. W. Skan, "Approximate methods for predicting separation properties of laminar boundary layers," *Aeronaut. Quart.*, Vol. VIII, pp. 257-268, 1957.
11. Garner, H. C., "The development of turbulent boundary layers," ARC R&M 2133, 1944.
12. Yang, S. L., et al., "Numerical Computation of the NREL airfoils using a symmetric TVD Scheme," as presented, 13th ASME/ETCE Wind Energy Symposium, 1994.
13. Somers, D. M., "Design and Experimental results for the S809 Airfoil," Airfoils, Inc., Hampton, Virginia, 1989.
14. Tu, Peter K. C., "Effects of Post-Stall Airfoil Characteristics on Predicted Rotor Performance," as presented, 13th ASME/ETCE Wind Energy Symposium, 1994.

15. Dini, P., et al., "Effects of Laminar Separation Bubbles and Turbulent Separation on Airfoil Stall," as presented, Windpower '92 Conference, (10/19-23,1991), Seattle, WA, 1992.
16. Coiro, D. P., and Dini, P., Stall and Post-Stall Performance Prediction of Advanced Wind-Turbine Airfoils, Associazione Italiana di Aeronautica ed Astronautica, XII Congresso Nazionale, 1993.
17. Schlichting, Hermann, *Boundary Layer Theory*, McGraw-Hill Book Company, New York, 1979.
18. Muesmann, H., "Zusammenhang der Strömungseigenschaften des Laufrades eines Axial-gebläses mit denen eines Einzelflügels" Diss., Braunschweig, ZFW 6, 345-362, 1958.
19. Preston, J. H., "The determination of turbulent skin friction by means of pitot tubes," J. Aero. Soc., 58, p. 109, 1954.
20. Young, A. D., *Boundary Layers*, Mackays of Chatham, Kent, Great Britain, 1989.
21. Bertin, John J., and Michael L. Smith, *Aerodynamics For Engineers*, Prentice Hall, Englewood Cliffs, N. J., 1989.
22. Tollmien, W., "Grenzschichttheorie." *Handbuch der Exper.-Physik IV, Part I*, 241-287, 1931.
23. Bass, R. M., "Propeller Performance Prediction and Design Techniques," Von Karman Institute for Fluid Dynamics Lecture Series 1982-08.

Appendix A

COMBINED EXPERIMENT TEST SETUP



